THE EXPERIMENTS ONBOARD THE ROSETTA LANDER

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Abstract. As a part of ESA's cornerstone mission "ROSETTA" to comet 46P/Wirtanen a 100 kg Lander will bring a scientific payload of almost 27 kg to the surface of the nucleus. After a first scientific sequence it will operate for a considerable fraction of the cometary orbit around the sun (between 3 AU and 2 AU). Ten experiments with a number of sub-experiments are foreseen; this paper presents the current status of the Lander development and reviews the scientific capabilities of each of the experiments at a time when the Flight Model (FM) of the Lander is already delivered.

Keywords: Comet nuclei, payload, space missions, Wirtanen

1. Introduction

The ROSETTA Lander mission will be the first to actually land on a comet's nucleus and to study it *in situ* for a period ofseveral months. The ROSETTA spacecraft (Lander+Orbiter) will be launched with an Ariane 5 from Kourou, French Guiana, in January 2003 and will approach comet 46/P Wirtanen in August 2011 (cf. Schwehm and Schulz, 1999). During its way to the comet the Lander will be mostly in hibernation mode. Occasional checkouts and magnetometer measurements (e.g., during asteroid fly-by) will be the only exceptions. After the rendezvous with the comet (at $\approx$ 4.5 AU) and about one year of observations with Orbiter instruments, a landing site will be chosen. The Lander will be activated and, after 7 days of delivery preparations, separated from the Orbiter with an altitude as low as possible, e.g., 1 km. Eject will be performed with lead screws with adjustable speed; under almost zero-g conditions a cold-gas push-down thruster and flywheel 1-axis stabilisation provide for a descent time of less than 3 hours and a hold-down thrust upon touch down on the comet. At touch-down with $\Delta v \approx 1$ m/s the Landing Gear will adjust itself to the terrain and dampen the impact momentum. At the same instant a harpoon connected to a tether is fired into the surface of the comet to anchor the Lander (see Ulamec, 1997a for a detailed discussion). On the comet the Landing Gear then provides for rotation, vertical adjustment and tilting of the Lander, thus the comet material can be probed on arbitrary positions on a working circle with a diameter of 0.8 m. The Lander subsystems are described in Ulamec et al. (1997b), Wittmann (1999).

The Rosetta Lander and its payload are designed to achieve the minimum mission goals within few days after landing, which will take place when the comet is at

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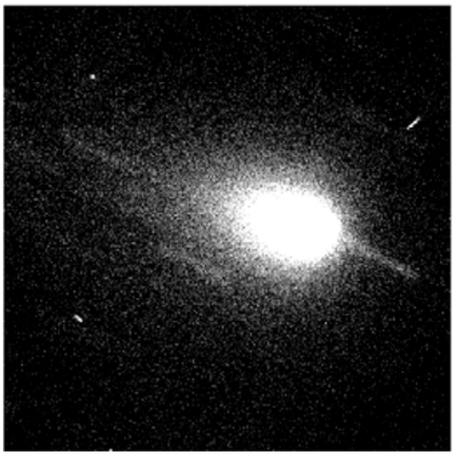

Figure 1. The target: groundbased image of Comet Wirtanen (courtesy Rita Schulz).

a heliocentric distance, $r \approx 3$ AU, presumably before the onset of any major cometary activity. Subsequently, the long-term mission will study the evolution of the comet's activity while approaching the sun. Here the ROSETTA project combines two strategies for characterizing the properties of the cometary nucleus: on one hand, the comet's evolution along the orbit with decreasing r will be investigated with the Orbiter instruments by monitoring the physical and chemical properties of the nucleus and in situ analysis of the near-nucleus environment. On the other hand, the Lander will provide ground truth by analysing the nucleus material directly.

The target comet, 46P/Wirtanen (see Figure 1) was discovered in 1948; it is a short-period comet with an orbital period of 5.46 years, aphelion and perihelion distances of 5.46 and 1.06 AU, respectively. Its peak gas production rate at perihelion is of the order of 10^{28} mol/s; it is a relatively small comet with a radius of barely 600 m (assuming an albedo of 0.04). The comet's rotation period is not very well known (between 6 h and 10 d) while its rotation axis is presently unknown. See also Schulz and Schwehm, 1999. Tables I and II give an overview on the mission profile (cf. Schwehm and Schulz, 1999) and Orbiter/Lander characteristics.

Figure 2 shows the actual ROSETTA spacecraft (FM) with the Lander (on top) attached.

2. Lander Payload

There are 10 experiments on board of the Lander including the drill, sampling and distribution system SD^2, which serves other instruments; some of the experiments consist of several units. Table III gives an overview of the experiments, explaining the abbreviations and listing the providers. The scientific capabilities of each experiment are described in the following sections. – As this paper is meant to review and

TABLE I
Mission profile

Date	
13 Jan. 2003	Launch (Kourou)
05/2005	Mars flyby, gravity assist
10/2005	Earth flyby, gravity assist
07/2006	Otawara flyby
10/2007	Earth flyby, gravity assist
07/2008	Siwa flyby
11/2011	Rendezvous with the comet
10/2012	Lander delivery ($r = 3$ AU)
02/2013	Nominal end of longterm Lander mission ($r = 2$ AU)

TABLE II
Orbiter and Lander characteristics

Orbiter	Lander
Launch mass: 2900 kg (payload : 150 kg + 100 kg (Lander), 1600 kg propellants for a $\Delta V = 2.2$ km/s) *Wing span*: 32 m (solar array: 5.7 kW @ 1 A.U., 0.4 kW @ 5.25 A.U.). No RHUs. *On board memory*: 42 Gb (solid state) – S&X-band TM/TC link *Industrial team*: DaimlerChrysler (prime) + MSS (platform and avionics) + Alenia (AIT)	*Overall mass*: 100 kg (payload 26.7 kg). Practically a small autonomous spacecraft *Energy/power* from primary batteries, solar array (about 10W at 3 a.u.) and secondary batteries. *On board memory*: 2*16 Mb *S band TM/TC* with the orbiter *Designed and developed* by an European consortium under German (DLR) leadership.

summarize the Lander's scientific payload, it cannot replace the original research papers, which are referenced at the end of each section.

2.1. APX

APX is an Alpha-Xray-Spectrometer for elementary analysis (all major elements except H, He). It irradiates the comet's surface with an alpha source (30 mCi, 96-Cm) and measures the spectra of backscattered alpha particles (Rutherford

TABLE III
Experiment overview

Acronym	Full Name	Principal Investigator (PI)
APXS	Alpha Proton Xray Spectrometer	R. Rieder, MPI Chem. Mainz, Germany
ÇIVA	Comet Nucleus Infrared and Visible Analyser	J.P. Bibring, IAS, Orsay, France
– P/S	– panoramic incl. stereo	
– M(V/I)	– Microscope (V = visual, I = infrared spectra)	
COSAC	Cometary sampling and Composition Experiment	H. Rosenbauer, MPAe, Katlenburg-Lindau, Germany
– MS	– Mass Spectrometer	
– GC	– Gas chromatograph	
– PG	– Pressure gauge	
CONSERT	Comet Nucleus Sounding Exp. by Radiowave Transmission	W. Kofman, CEPHAG Grenoble, France
MUPUS	Multi-Purpose Sensors for Surface and Sub-Surface Science	T. Spohn, Univ. Münster, Germany
– PEN	– Penetrator	(SRC Warsaw)
– TM	– Thermal Mapper	(DLR Berlin)
– ANC	– Anchor sensors	(IWF Graz)
MODULUS/ Ptolemy	Method Of Determining and Understanding Light elements from Unequivocal Stable isotope compositions	I. Wright, Open University & Rutherford Appleton Laboratories, UK
– MS	– Mass Spectrometer	
– GC	– Gas chromatograph	
ROLIS	Rosetta Lander Imaging System	S. Mottola, DLR Berlin, Germany
ROMAP	Rosetta Lander Magnetometer and Spectrometer	U. Auster, MPE Munich and TU Braunschweig, Germany
SESAME	Surface Electrical, Seismic and Acoustic Monitoring Exp.	D. Möhlmann, DLR Cologne, Germany
– CASSE	– Comet Acoustic Surface Sounding Experiment	– DLR Cologne, Germany
– DIM	– Dust Impact Monitor	– I. Apathy, KFKI, Hungary
– PP	– Permittivity Probe	– W. Schmidt, FMI Finland
SD^2	Sample Drill and Distribution	Politecnico of Milan

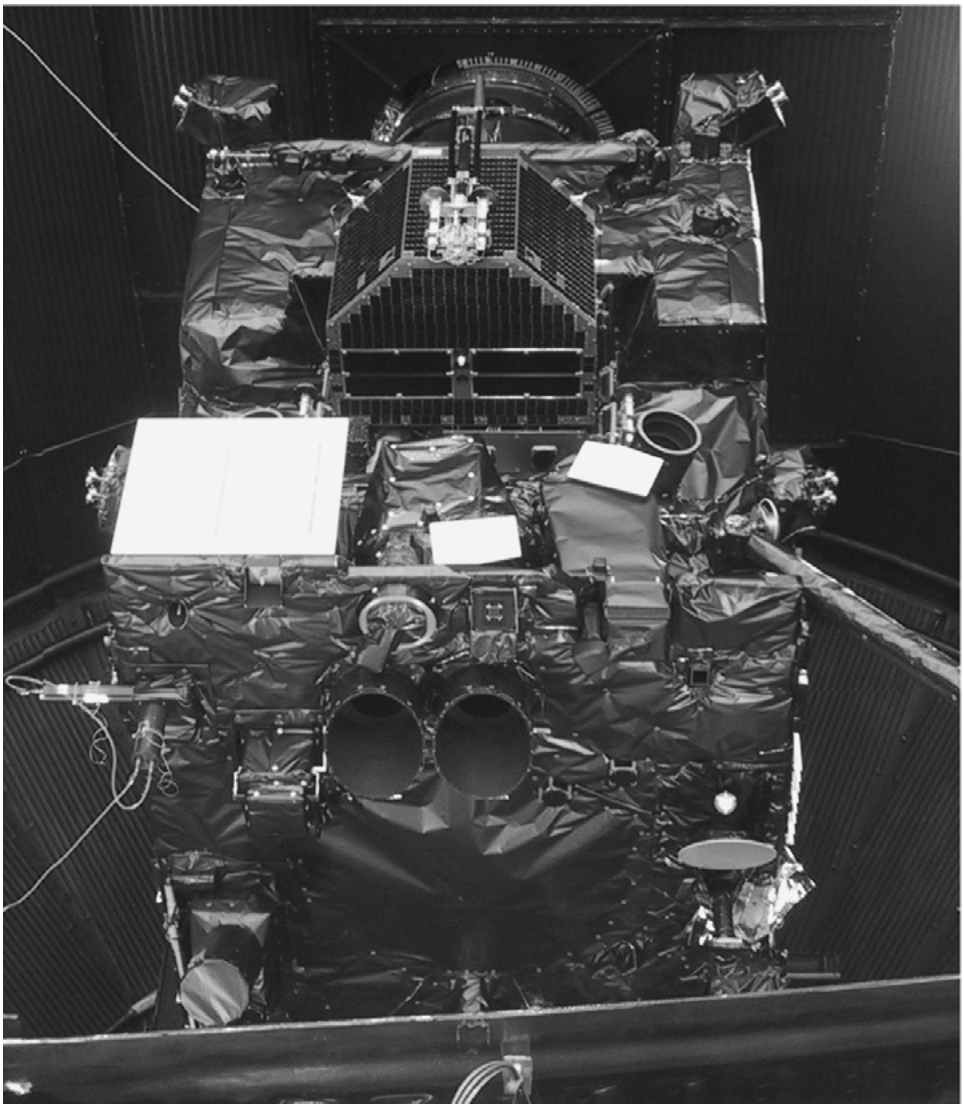

Figure 2. The Lander mounted on top of the ROSETTA spacecraft while being installed in the thermal vacuum chamber at ESTEC, February, 2002.

scattering) and alpha-induced characteristic X-ray radiation. The design of the Rosetta Lander APX spectrometer is based on the experience gained with the APX spectrometers built for American and Russian Mars missions (Rieder et al., 1996).

The APXS provides information on the elemental composition of the material underneath the Lander which cannot be derived from the results of the more sophisticated evolved gas analysers (EGAs) because many elements may not be represented in the volatile fraction with their true abundance (the elemental and isotopic composition together should provide clues to the basic question of the comets origin). Only the composition of the uppermost atomic layers is determined by APX; the disadvantage is that these layers cannot be expected to show the composition of the bulk material. However, under sunlit conditions, the composition of the non-volatile fraction is probably well represented. Hence dynamic day/night changes in composition can be studied via the recondensation of volatiles at the surface (frost) which could happen in the "evening" and during "night". – The mechanism lowering the APXS to the optimum distance to ground (4 cm) is also used to get a ring in contact with the surface serving as the fourth electrode for the SESAME permittivity probe.

For more information on APX see (Rieder et al., 1996, 1997, 2000; Linkin et al., 1996; Economou et al., 1996, 1997).

2.2. ÇIVA

ÇIVA is an integrated set of imaging instruments, designed to characterise (1) the landing and sampling site, (2) the 360°panorama as seen from the Rosetta Lander, (3) samples collected and delivered by SD^2. It consists of a panoramic and stereo camera set (ÇIVA-P), and a microscope camera coupled to an IR spectrometer (ÇIVA-M(V/I)), sharing a common Command and Data Processing Unit (CDPU) with a 16 Mbytes mass memory (Beauvivre et al., 1999).

ÇIVA-P will characterise the landing site, from the landing legs to the local horizon. The camera system is composed of 5 identical cameras (5 mono cameras), mounted on the Lander sides plus a pair of the same micro-cameras (the stereo pair) at the balcony side of the Lander with their optical axes separated by 60°. Thus, 360°can be viewed at a time with the balcony side of the Lander being stereo-imaged. Lander rotation and repetitions of ÇIVA-P operations several times along the cometary activity will allow to characterise the 3-D surface topography, provide an albedo mapping of the landing site and detect manifestations of cometary activity and resulting surface changes at scales not achievable from the Orbiter.

The seven camera heads contain 6 elements objectives and 1024x1024 frame transfer CCD detectors and will be operated sequentially. The electronics driving each CCD has adequate intelligence to optimise the exposure time. All images will be compressed and stored before being transmitted, via the ROLIS DPU (see sec. 2.7), to the CDMS.

ÇIVA-M combines an ultra-compact and miniaturised visible light microscope (-M/V) and coupled IR spectrometer (-M/I), to characterise, by non-destructive analyses, the texture, albedo, mineralogical and in part also the molecular composition of the samples collected and distributed by SD^2. The resolution of ÇIVA-M/V images is 14 μm; the samples are illuminated sequentially with 3 LEDs of different colours. Following the microscope imaging, IR spectral images will be obtained, with a spatial resolution of 50 μm, with a 128 x 128 IR HgCdTe array operating at temperatures 120 to 170 K. The samples are illuminated by a monochromator operating between 1.0 and 4.0 μm at a resolution of 5 nm, using a rotating grating. The spectrometer should allow identifying the major organic chemicals in the volatiles and organic refractories. The entire process will take less than 5 minutes, to get all spectra with SNR $>$ 100, assuming IR albedos of 0.05. Then, the sample can be transferred to a subsequent experiment (COSAC or PTOLEMY). The process may be repeated for each sample obtained at different depths and/or location.

2.3. COSAC

The scientific goals of COSAC are: the identification of natural and pyrolytically generated volatile compounds and their parent molecules with emphasis on organic, potentially "pre-biotic" material. A special effort is devoted to chiral compounds with the objective to look for deviations from homochirality which is characteristic of life on Earth. The method: Cometary material from both the natural surface below the Lander and the ground of drill holes (collected immediately at and up to $\sim$20 cm below the surface, provided by the SD^2 instrument (see sec. 2.10) is heated in steps up to 800°C. The evolving gases are analysed employing gas-chromatographic and mass-spectroscopic (GC/MS) methods.

The gas chromatograph (HETP$<$ 2mm) and the mass spectrometer will normally be used in a coupled mode. The separation and identification, respectively, of isobaric molecules is mainly accomplished by means of a high-resolution time-of-flight mass spectrometer ($M/\Delta M > 3000$ in a high-resolution mode, $\approx$ 300 in low-res mode for M up to about 7000, sensitivity better 100 ppm, almost noise-free detection) employing a special geometry of synchronous ion trajectories allowing for long paths despite a small instrument dimension (multiple reflections). Many chemical compounds and their chiral properties and isotopic ratios can be separated and detected in a quantitative way. COSAC also comprises a pressure gauge (one Penning, one Pirani sensor) to measure the cometary atmosphere's pressure in the range 10^{-7} to 1 mbar. For further reference, see Rosenbauer et al. (1999).

2.4. CONSERT

With the CONSERT experiment the internal structure of the nucleus can be probed. A transmitter on the Orbiter sends wave packets through the nucleus to the Lander, which returns them back in a transponder manner. The measured dielectric properties of the nucleus constrain the composition and can detect large-size structures and stratification. The scientific objectives of the CONSERT experiment on the ROSETTA mission are described in Barbin et al. (1999) and Kofman et al. (2002). The experiment uses a wide bandwidth signal, which will allow measurements of the signal propagating through the main and secondary paths. These measurements will also provide the distribution of the secondary path for a deeper description of the comet interior and better spatial coverage. In order to process the signal globally, i.e., to combine the measurements corresponding to the different position on the orbit, the signals on the Orbiter and on the Lander must be coherent with stable relative phase and have a good signal to noise ratio. These conditions had put constraints on system structure, clock stability, antennas and operations which were all met. For further reference, see Benna et al. (2001).

2.5. MUPUS

The Multi-Purpose Sensor Experiment MUPUS consists of three parts:

1. A penetrator, PEN, $\approx$ 40 cm long, that will be hammered into the ground about 1m away from the Lander. During the penetration process the mechanical strength of the material will be measured by means of a depth sensor and a densitometer. The penetrator is equipped with a series of temperature sensors for determining the temperature as a function of depth and insulation. The temperature sensors can also be used as heaters which will allow to measure the thermal conductivity of the surrounding material (Seiferlin et al., 1996). PEN also carries the fifth electrode for the SESAME permittivity probe.
2. An accelerometer and a temperature sensor accommodated in the harpoon(s) will allow thermal and strength measurements to (probably) larger depths than the PEN. The accelerometer measures the impact profile when the harpoons are shot (at touchdown) and from which mechanical properties of the material penetrated can be reconstructed.
3. A four-channel infrared radiometer (MUPUS-TM) measures surface temperatures in the vicinity of the Lander. An accuracy in the order of 1..10 K is envisaged, while the resolution is better than 0.1 K. For further reference see Seiferlin et al. (1996, 2000).

2.6. MODULUS/PTOLEMY

This instrument consists of an ion trap mass spectrometer designed for isotope analysis and to determine qualitative analytical data; chemical separation of isobars (δ to $\pm 0.1\%$ for H, C, N, O) will be done by gas chromatography. The mass spectrometer will operate in the range 10–200 AMU with better than unit mass resolution (in isotope mode: 3 times better). Operation: Like for COSAC, the sample volatiles are analysed by heating the oven where they are quantified, purified and chemically reacted (if necessary) to produce a relatively simple gas mixture. Gases are then passed to the ion trap mass spectrometer, either directly or through one of three analytical channels comprising gas chromatography columns and additional chemical processing reactors. For experiments requiring gas chromatography a constant supply of the helium carrier gas is delivered by a regulated supply, which ensures maintenance of the necessary pressure and flow-rate. In either mode of operation (direct, or chromatography) the ion trap mass spectrometer is set to perform continuous sweeps over the mass range of interest. Since Ptolemy aims to obtain isotope ratio measurements of the highest possible precisions, the ion trap instrument will be calibrated in situ during the same period of time over which the cometary analyses are made. For this, equivalent analyses will be made of a reference gas taken from Earth to the comet and delivered to the instrument through the gas management system. In this way analogous isotope ratio data will be acquired from the reference gas. With knowledge of the actual isotopic ratio of the reference it will then be possible to correct the measured cometary data in order to obtain an absolute value for the ratio of interest. More details can be found in Wright and Pillinger (1998) and Wright et al. (2002).

2.7. ROLIS

ROLIS is a miniature CCD imager (1024 × 1024, focal length 12 mm) located on the balcony of the Rosetta Lander and oriented in a downward-looking direction. From this position ROLIS can observe a region of about 30x30 cm of the nucleus surface located below the Lander with a spatial sampling of 0.3 mm/pixel. In order to illuminate the field to be imaged, ROLIS incorporates four independent arrays of light emitting diodes (LEDs) irradiating through the visible and near IR, in spectral bands centred at about 470, 530, 640 and 870 nm with a FWHM of about 100 nm. ROLIS will also operate during the descent phase, acquiring images of the landing site and its vicinity shortly before touch-down. Due to its location on the so called "instrument common working circle", ROLIS can inspect the sampling sites of the "in situ" Lander analysers, before and after the drilling operation. In addition to gathering surface colours and morphology, imaging of the bore-hole sides can possibly reveal signs of stratification, or give clues about the mechanical strength of the surface layer. During the extended mission ROLIS will search for signs of evolution of the surface features as the comet approaches the Sun. Both ROLIS and ÇIVA are managed on board by a common "Imaging Main Electronics", ROLIS-IME; wavelet transformation data compression ($>$1:10) is used for both instruments. See also Mottola et al. (2002).

2.8. ROMAP

Romap comprises a magnetic field sensor (MAG) and a plasma monitor (SPM). It's main scientific goals are long-term magnetic field and plasma measurements of the surface of Comet 46P/Wirtanen in order to study cometary activity as a function of heliocentric distance, and measurements during the Lander's descent to investigate the structure of the comet's remnant magnetisation. MAG and SPM complement the plasma packages aboard the Rosetta Orbiter. Both instruments investigate the comet/solar wind interaction, cometary activity and the onset of diamagnetic cavity formation. Specifically, SPM measures the major solar wind parameters such as density, speed, temperature and flow direction, while MAG determines the magnetic field vector. The ROMAP fluxgate magnetometer, electrostatic analyser and Faraday cup measure the magnetic field from 0–64 Hz, ions of up to 8000 keV and electrons of up to 4200 keV. For MAG, dynamic feedback fields as well as offset fields of up to 2000 nT can be generated to compensate for Lander and/or Orbiter DC stray fields. The SPM sensors are active in the surface mode only. In this mode, MAG and SPM work sequentially. During Rosetta's cruise phase and during the Lander descent, ROMAP will measure in the slow (1 Hz) magnetometer mode. Particularly during periods when the spacecraft is active (e.g., before and during asteroid flybys), magnetometer data from ROMAP will help to distinguish between external fields and spacecraft disturbances. The 'fall off' profile during descent will provide reliable information about the comet's internal magnetic structure, if any. SPM will start its measurements some minutes after landing. After a short initial measurement interval of 20 min, measurement cycles lasting typically 4 h are expected for the long-term mission on the surface. The fast magnetometer mode (64 Hz sampling rate) will be used only for measurements in parallel with the Permittivity Probe (E-field) of the Lander's SESAME-PP instrument (see below). Further details can be found in (Auster, 2002).

2.9. SESAME

2.9.1. *SESAME-CASSE*

The CASSE instrument is developed to study by acoustic sounding the mechanical properties of the upper surface layers of the comet. It consists of piezoelectric actuators (transmitters) and sensitive accelerometers (sensors) in the "feet" of the Landing Gear. The near-surface structural properties and the layer structure of the soil will be determined by acoustic and seismic probing (active and passive). The measurements can be used to improve the modelling the surface layers and their influence on cometary outgassing.

2.9.2. *SESAME-PP*

PP sounds the permittivity properties of the surface electromagnetically. Five electrodes, three at the Landing Gear's "feet" and two at the MUPUS-PEN and APX deployables, are used to probe the soil with a quadrupole array technique at various frequencies, measuring the complex permittivity, i.e., electrical conductivity and dielectric polarizabilitiy down to a depth of a few meters. With these measurements the water content (distribution of polar molecules) and its variation can be studied. In passive mode, the experiment has the additional capability of a plasma wave investigation: it detects the electric fields of electrostatic and electromagnetic waves with frequencies up to 10 kHz, which are generated by the interaction of the solar wind with the charged dust and ionized outgassing products of the nucleus. By sampling the total intensity of plasma waves every few second, these measurements will consequently provide a continuous monitoring of the nucleus activity. For further reference, see Grard et al. (1996).

2.9.3. *SESAME -DIM*

DIM is a three-dimensional dust-impact monitor. While larger particles will be sensed by the CASSE receivers in the Lander's feet, DIM will investigate the flow of small particles hitting the Piezo-sensor plates of this instrument. For a more detailed discussion of the SESAME sub-experiments, see Möhlmann (2002) and Kochan et al. (2000).

2.10. SD^2

The Sampling, Drill & Distribution System is capable of drilling and sampling anywhere on a circle of about 0.4 m radius around the Lander's rotation axis up to a drill depth of 25 cm. Drilling in material with a compressible strength of up to 3 MPa (equivalent to solid ice with stony inclusions) has been demonstrated. A sample (6–34 mm^3) can be gauged with the Volume Checker and be transferred to a carousel containing 28 Medium- and High-Temperature ovens (the former equipped with sapphire windows to allow optical and IR spectroscopic observations by ÇIVA-M-V/I) serving the two EGAs by means of resealable Docking Stations.

3. Mission Operations and Timeline

After commissioning only one operation is currently foreseen before the comet mission, which is a ROMAP magnetometer measurement during the asteroid 140 Siwa flyby. At the comet, one distinguishes between the first scientific sequence and the long-term mission.

3.1. FIRST SCIENTIFIC SEQUENCE

This high-priority sequence is foreseen to fulfil the minimum scientific requirements under worst-case circumstances (e.g., no energy from solar cells). All short term science investigations are completed once within the first 120 h after touchdown including the drilling and analysis of 4 samples (two surface and two sub-surface). The results of the surface sample analysis and the panoramic images are sent as soon as possible to ground in order to be analysed on Earth and permit an optimisation of the ongoing first sequence (optimum orientation of Lander to the sun, attitude for deployment of MUPUS-PEN and APX). A strawman mission timeline for the first ca. 51 h after separation has been worked out and proves to be compatible with energy, power and telemetry constraints. During the first 60 h at least one full orbit of Rosetta shall be dedicated to perform CONSERT operations.

3.2. LONG-TERM MISSION

The long-term mission is baselined from $r = 3$ AU to $r = 2$ AU (corresponding to a period of about 3 months); it is foreseen to map the evolution of the comet's activity with changing heliocentric distance. During this period the Lander will perform mostly serial operations, relying entirely on the solar generator. Long term, low-power experiments like SESAME, MUPUS and ROMAP can be turned on periodically, while others, like COSAC and PTOLEMY, will analyse samples whenever the energy budget will allow to do so. The exact operational sequence will be worked out interactively.

3.3. EXTENDED MISSION

At some stage 1 AU $< r <$ 2 AU the Lander will overheat or be covered with dust defining the point where any extended mission will definitely end.

3.4. THE ROSETTA LANDER GROUND SEGMENT

This ground segment consists of the Rosetta Lander Science and Navigation Centre, SONC, (CNES) and the Rosetta Lander Control Centre, LCC, (DLR Cologne), jointly commanding the Lander via the Rosetta Mission Operations Centre (ESOC) and the Perth 35m ground station.

4. Schedule, Status and Outlook

The Lander Flight Model (FM) has been delivered to ESA and is undergoing extensive system tests. A Ground Reference Model (GRM) will be build by summer 2002 and the Lander Software testbed development is ongoing. Only one descope action (MUPUS PEN densitometer) had to be performed; mass and telemetry budgets are under control, and the energy budget will be improved by implementing additional batteries. However, refurbishment actions, critical system tests and verifications are still ahead.

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